# Coherent Neutrino-Nucleus Scattering

**Samuele Sangiorgio**
LLNL Advanced Detector Group

**Intensity Frontier**
**Neutrino Subgroup Workshop**

**SLAC, Mar 6, 2013**

Lawrence Livermore National Laboratory

LLNL-PRES-XXXXX
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# CNNS workshop in Livermore on Dec 2012

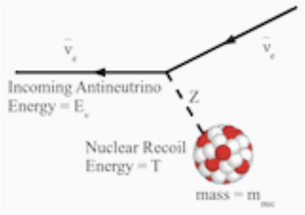
This presentation draws from talks and discussions from the recent workshop on CNNS held in Livermore.

http://neutrinos.llnl.gov/LLNL_CNS.html

Applied Antineutrino Physics

Lawrence Livermore National Laboratory    Sandia National Laboratory

Producing Antineutrinos | Detecting Antineutrinos | Monitoring Reactors | IAEA Reactor Safeguards | The LLNL/SNL Detector | Publications




**The Lawrence Livermore National Laboratory and Sandia National Laboratories Coherent Neutrino Nucleus Scattering Workshop**

**Dec. 6-7, 2012**

**Livermore Valley Open Campus, Livermore California**

**Adam Bernstein, David Reyna**

Workshop Agenda including Presentations

Link to agenda and slides

**Workshop Overview:**

On Dec 6-7 2012, a workshop was held at the Livermore Valley Open Campus on progress towards direct experimental measurement of neutrino scattering using neutron spallation and reactor neutrino sources.

Coherent scatter is a robust prediction of the Standard Model of particle physics, which has however eluded detection for 40 years, since i predicted in the 1970's. The workshop brought together many of the world's experts in coherent scatter detection, drawn from the dark mat neutrino physics communities, which community share common experimental goals. Presentations were made on argon, xenon, german

# Coherent Neutrino Nucleus Scattering

CNNS a neutral current process where an incoming neutrino elastically scatters on a nucleus

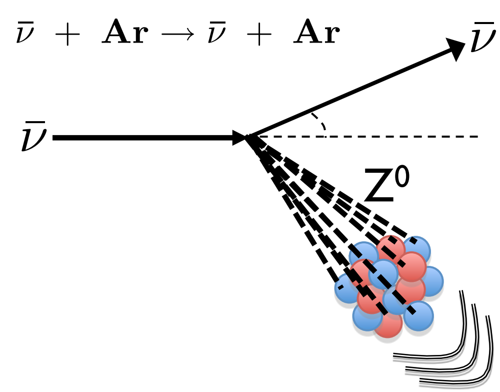
- undisputed prediction of the Standard Model
- enhanced cross-section:

Limit of zero-momentum transfer

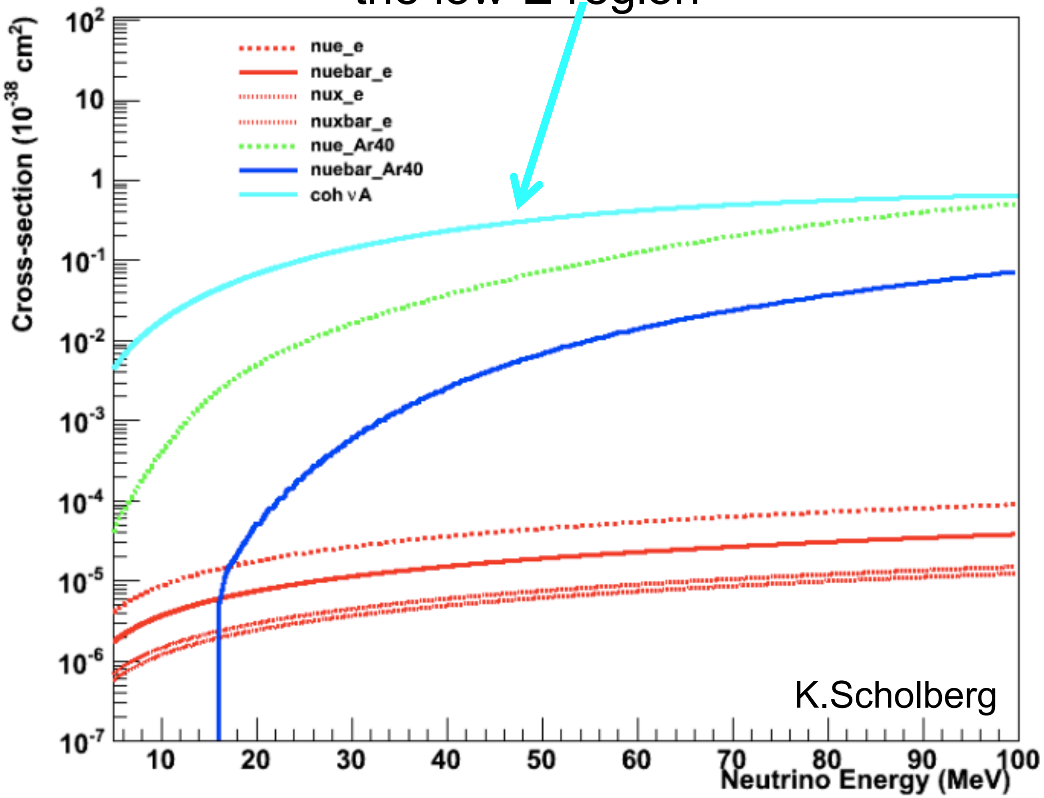
$$\frac{d\sigma}{d(\cos\theta)} \approx \frac{G^2}{8\pi} N^2 E^2 (1+\cos\theta)$$

- flavor independent
- coherence conditions:

$$E_\nu < \frac{1}{R_N} \simeq 50 MeV$$




Largest cross section in the low-E region



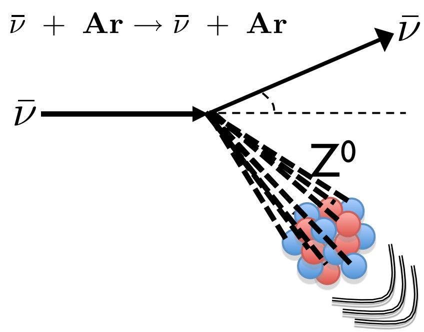

D. Z. Freedman Phys. Rev. D 9 (1974)

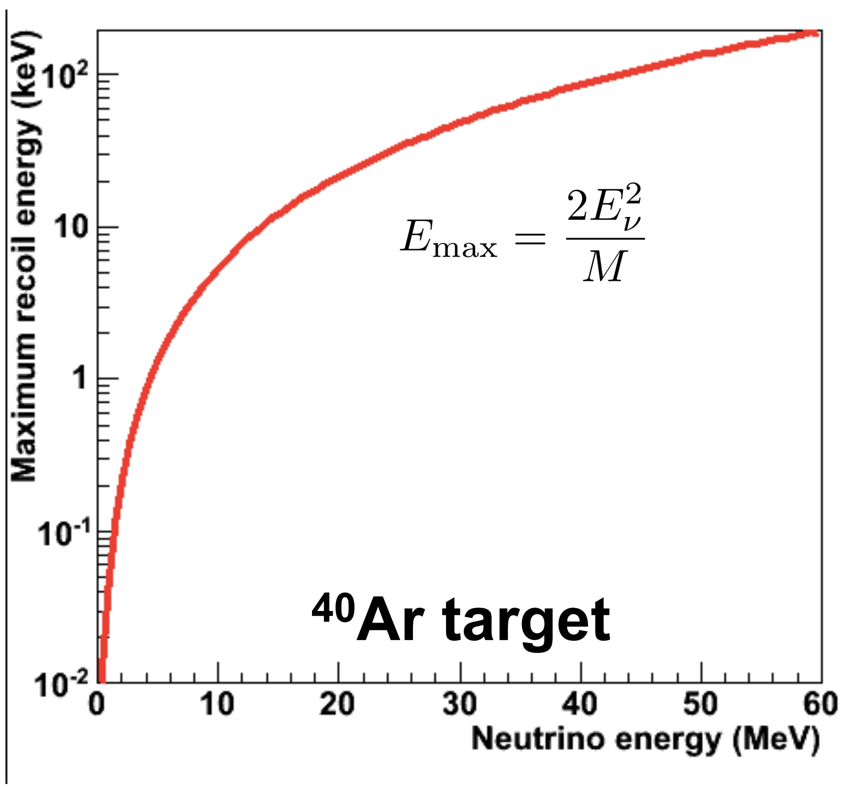
# CNNS detection: "An act of hubris"

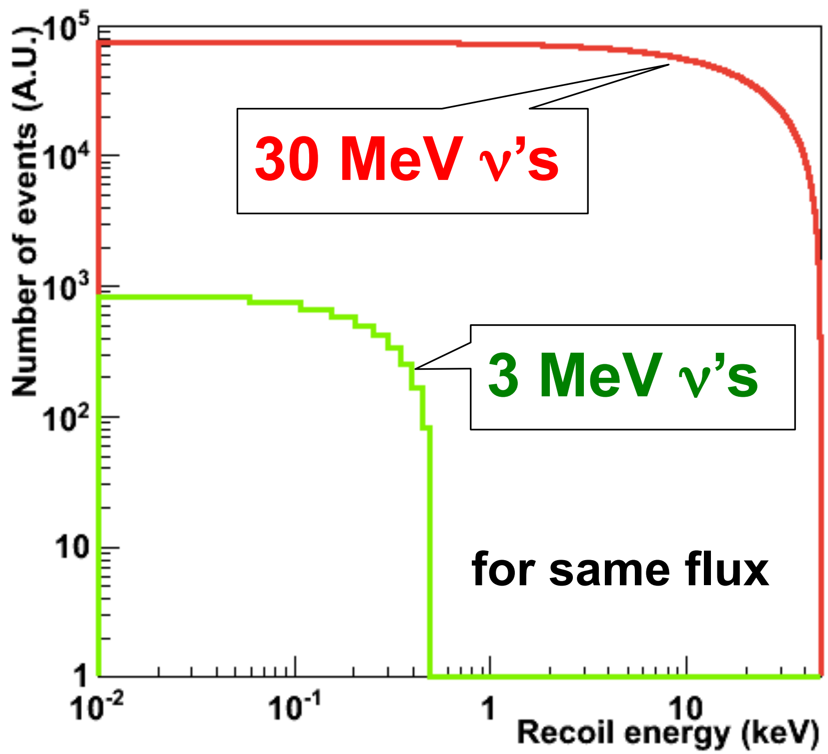
Still undetected 35 years after first prediction

- observable: tiny nuclear recoil

$$\langle E_r \rangle = 716\,\mathrm{eV}\,\frac{(E_\nu/\mathrm{MeV})^2}{A}$$




K.Scholberg

# The Scientific Reach of CNNS

- Discovery!
- Weak mixing angle
- Non Standard Interaction of ν
- Magnetic ν moment
- Sterile neutrinos
- Neutron form factor
- Supernovae
- Synergies with Dark Matter searches

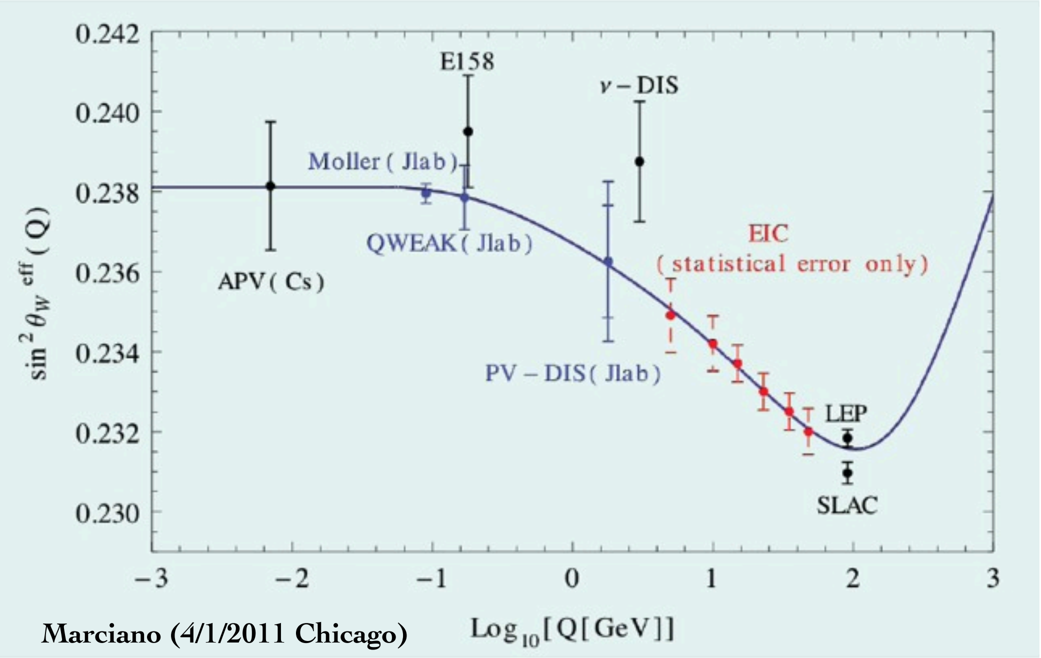
Tests of the SM

# Tests of the Standard Model

- **Weak mixing angle** L.M.Krauss, Phys. Lett B 269 (1991)

$$\text{rate} \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

- Might not be competitive, depending on approach and control of systematic.
- Unique channel
- Improve w/ multiple targets

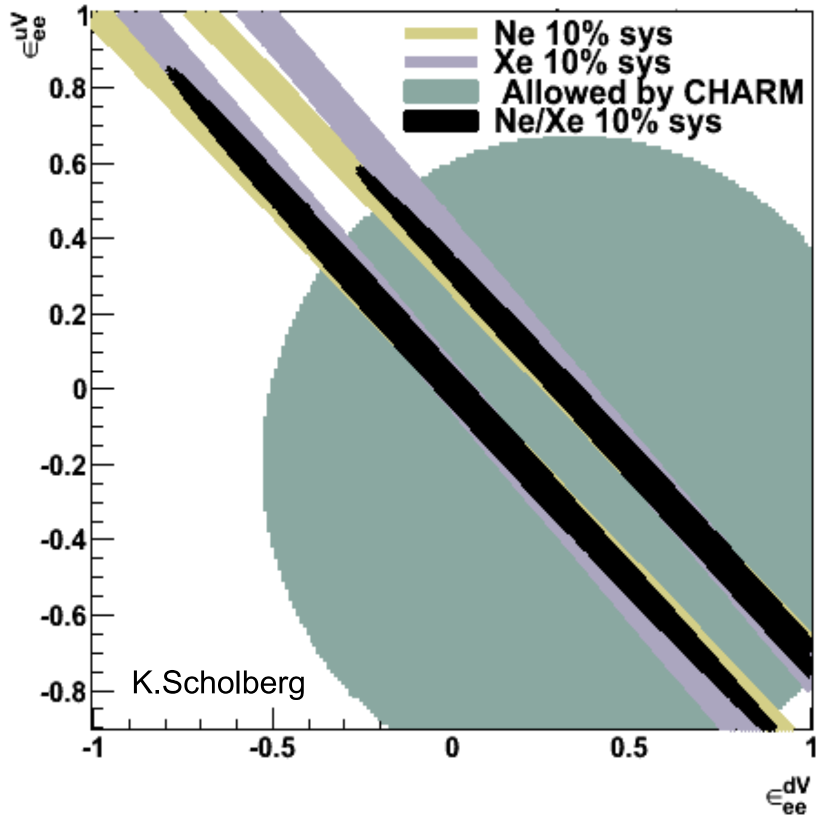


# Tests of the Standard Model

## ▪ Non Standard Interaction of ν

K.S. Scholberg, PRD 73, 2006
J. Barranco, PRD 76, 2007

- Sensitive to non-universal parameters
- Signature is a deviation from the expected cross-section
- Could significantly improve current constraints



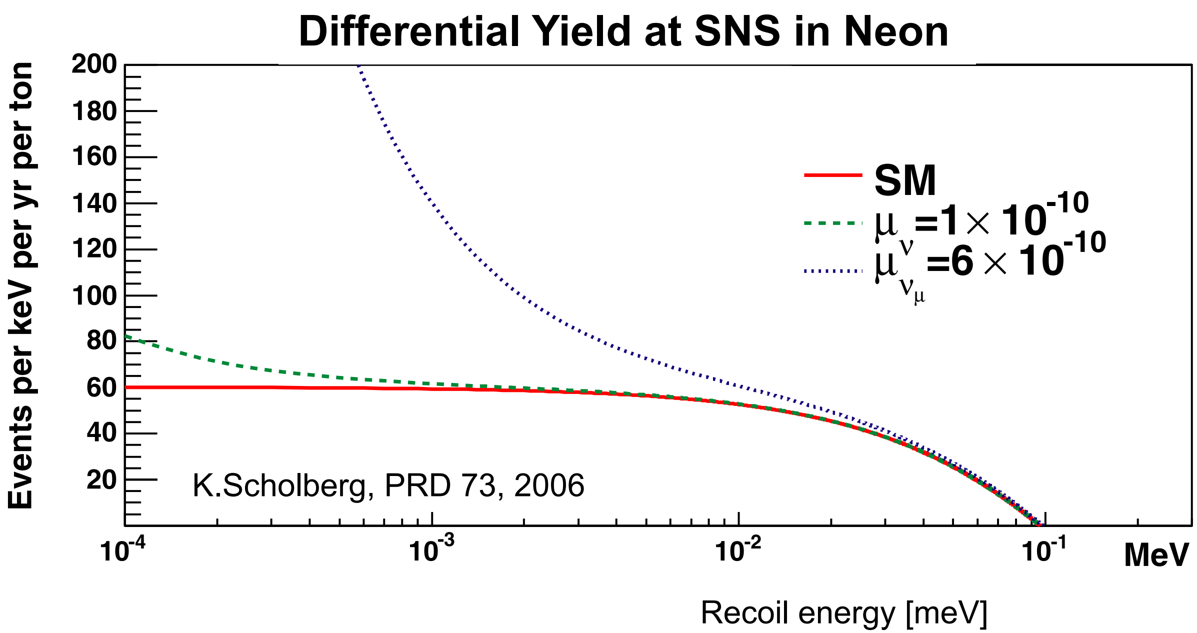

Link w/ subgroup nu5

# Tests of the Standard Model

- Magnetic ν moment

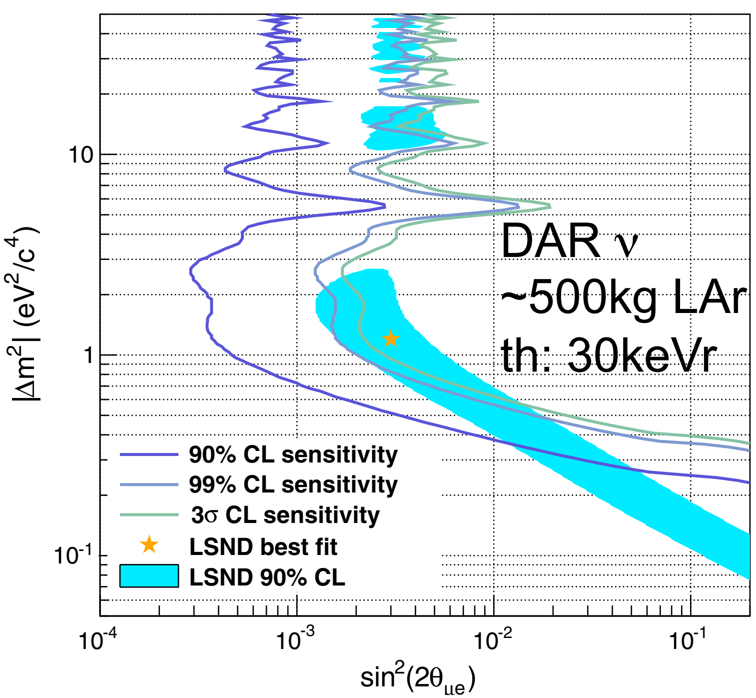
P. Vogel, J. Engel, PRD 39 (1989)

- Distortion of the recoil spectrum at low E
- Need detector w/ < 10 keV threshold



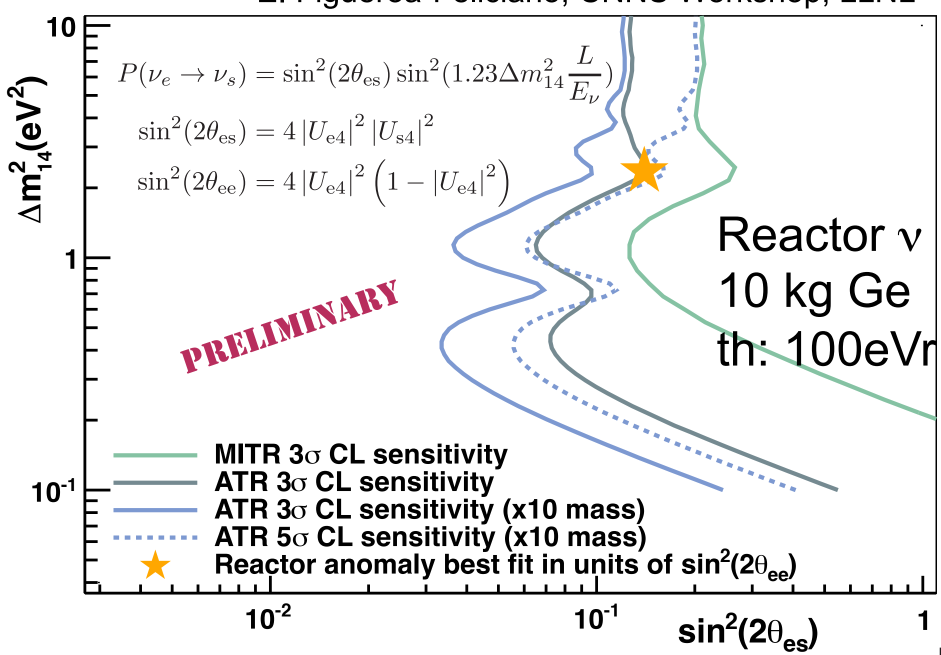
# Sterile Neutrinos

- CNNS is flavor independent
- Look for deficit of neutrinos
- Different approaches considered:
  - Movable detector at a reactor
  - Cyclotrons at different baselines (DAEDALUS)
  - Oscillometry using mono-energetic ν source



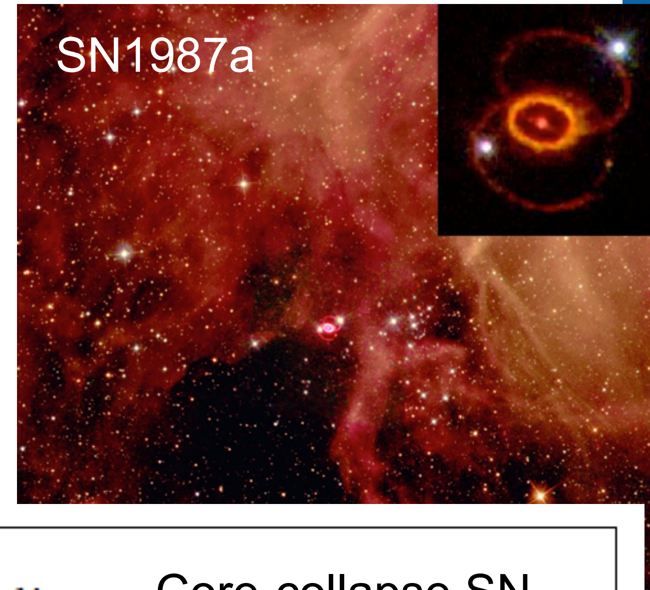

A. J. Anderson et al, PRD 86 (2012)

E. Figueroa-Feliciano, CNNS Workshop, LLNL

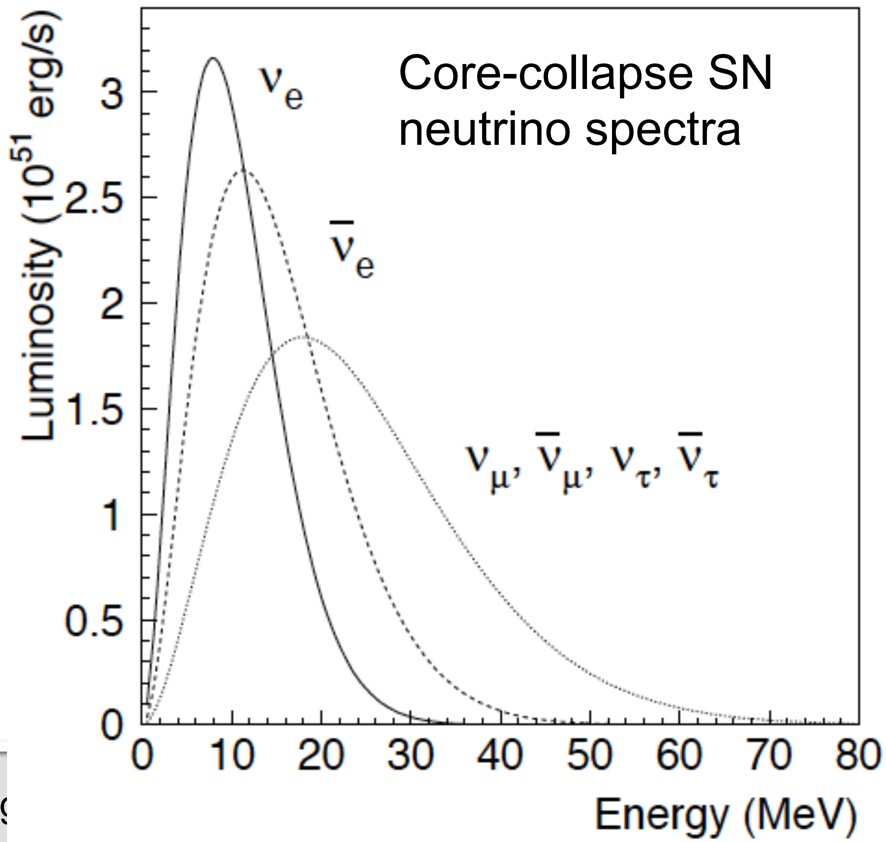


# Supernovae

- Neutrinos carry 99% of the energy in core-collapse SN
- CNNS plays important role in supernovae explosion → $\nu$ trapping in collapse phase
- Neutrinos help understand SN processes
- CNNS is sensitive to all flavors!




SN detection via CNNS:
~ 10 events/ton on Ar
in 10 s for galactic SN at 10 kpc



# Neutron Form Factor

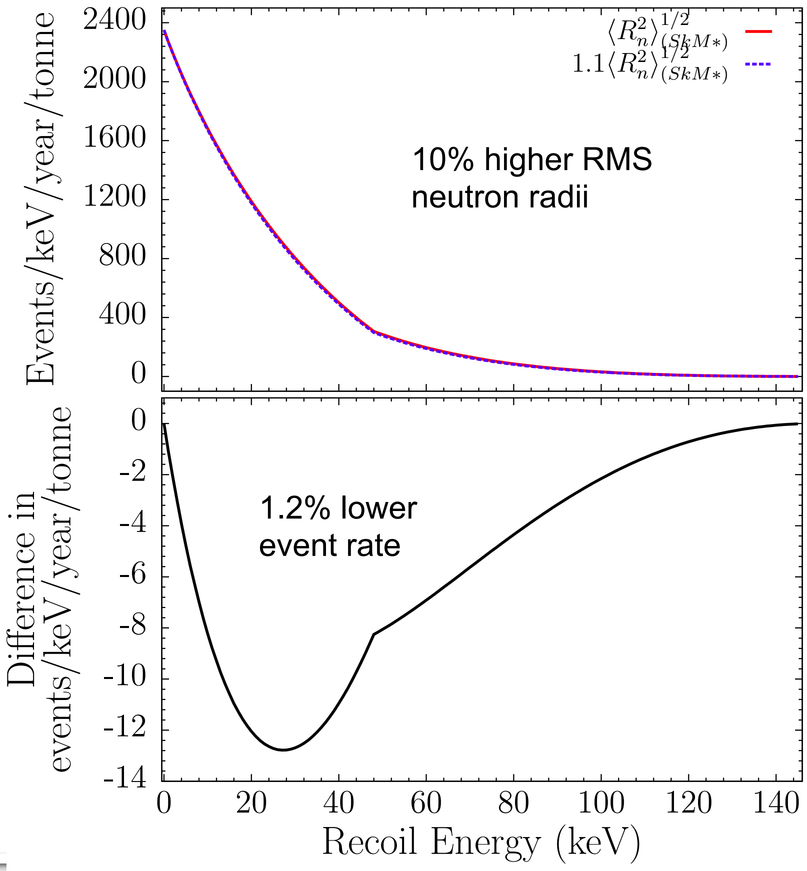
K. Patton et al, arXiv:1207.0693

- CNNS form factor mostly due to neutron distribution
- Requires 10-50 MeV neutrinos, good energy resolution and control of systematics

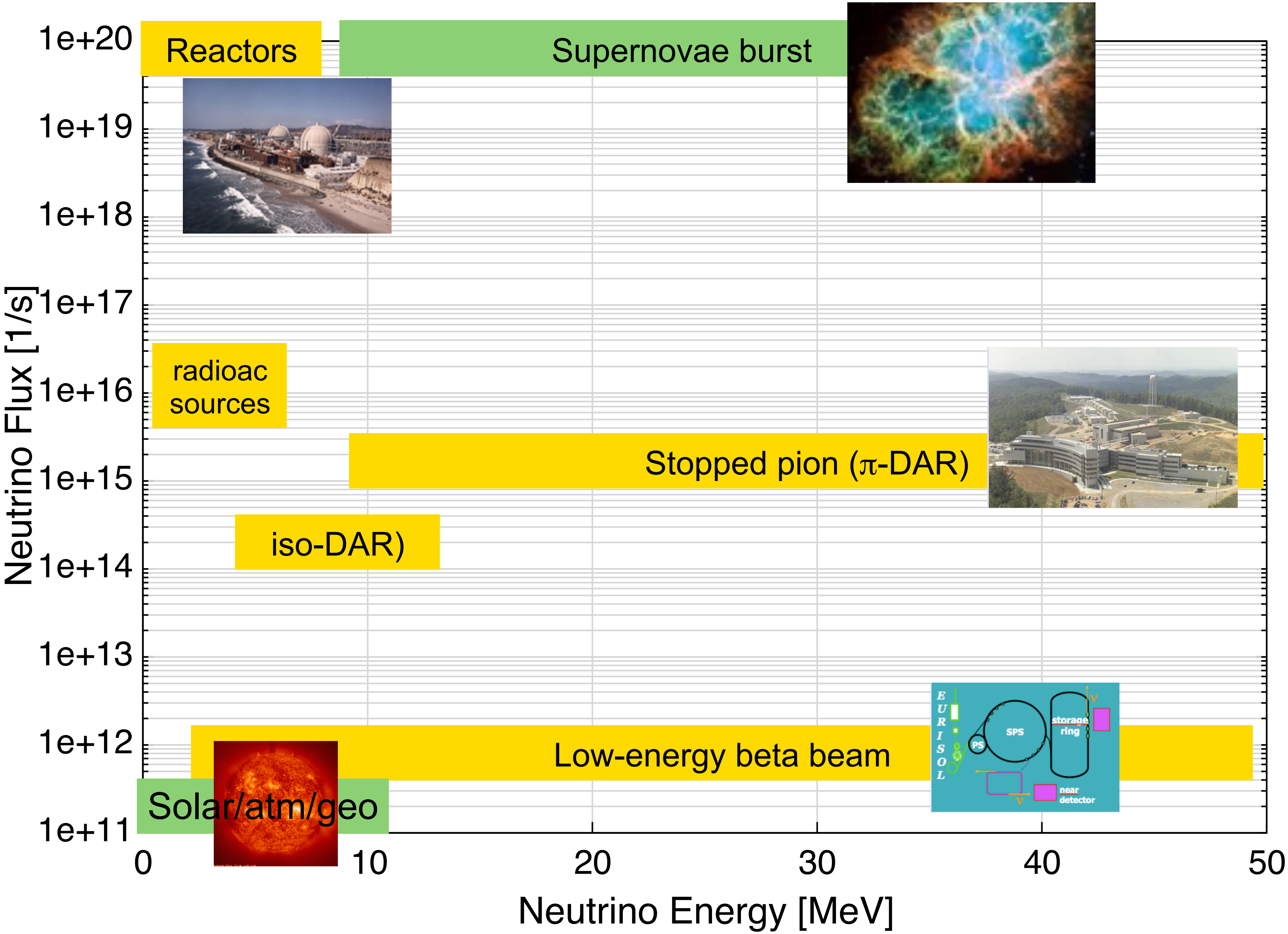
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

$$F_n(Q^2) \approx \int \rho_n(r) \left(1 - \frac{Q^2}{3!} r^2 + \frac{Q^4}{5!} r^4 - \frac{Q^6}{7!} r^6 + \cdots\right) r^2 dr$$

SNS neutrinos on Ar40



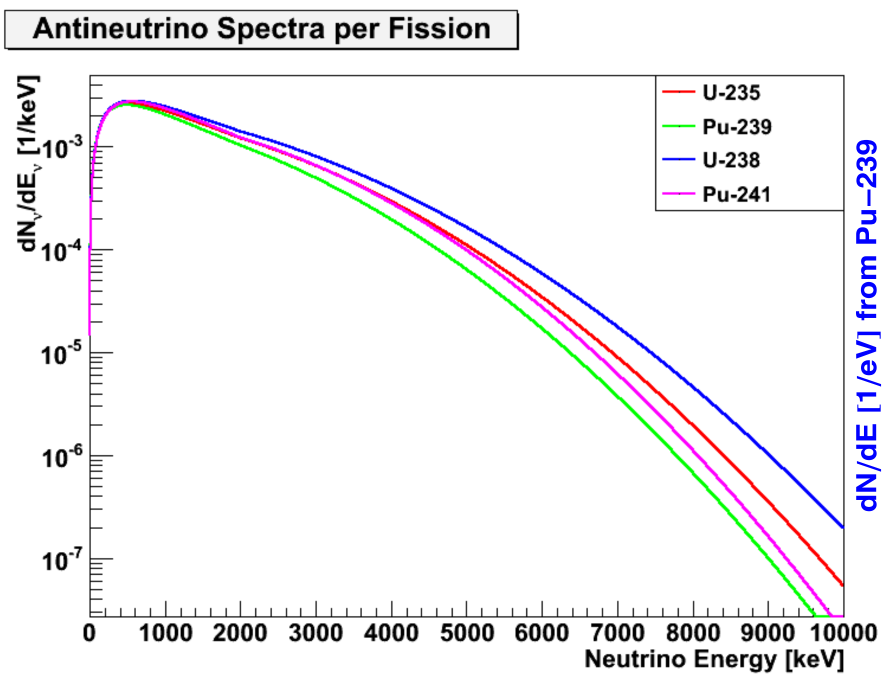
# Neutrino Sources in CNNS Energy Regime

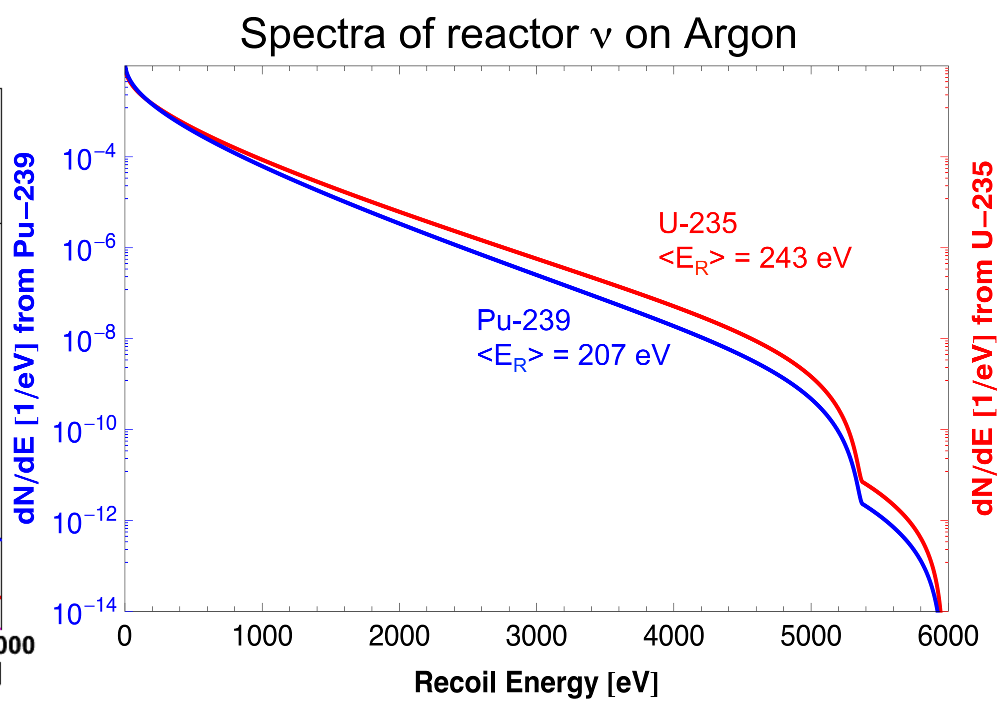


# Reactor Neutrinos

- Purely $\overline{\nu}_e$
- Free
- High Flux: ~$10^{21}$ $\nu$/s in a 3GWt reactor
- Low E → small recoils

- Little control over on/off cycle
- Shallow detector location
- Difficult site access and infrastructure but successfully demonstrated



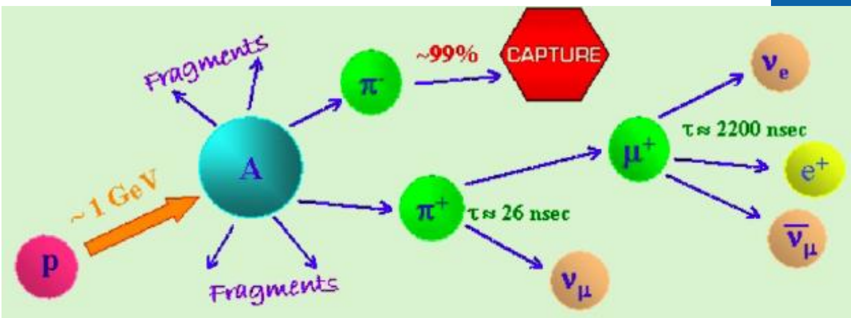



# Decay-At-Rest ν Production

- Multiple ν flavors, high E
- Flux: ~$10^{15}$ ν/s
- ν spectrum similar to SN
- Background control from beam pulsing but fast n need study
- Deployment?
- Locations/Concepts:
  - SNS @ ORNL
  - BNB @ FNAL
  - DAEDALUS
  - …

Proton energy < GeV to avoid Kaons production

iso-DAR → Li-8 decay



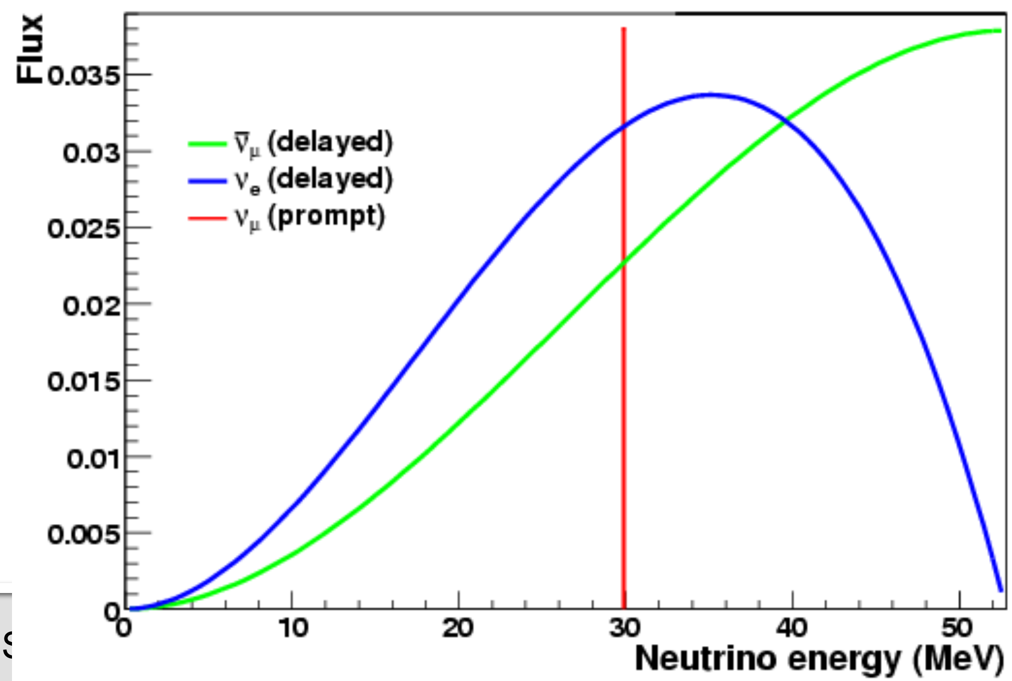

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

monocromatic 29.9MeV
PROMPT emission

$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay
Delayed emission (2.2μs)



# Reactor vs DAR

From WP:

**Perspectives to search for neutrino-nuclear neutral current coherent scattering**

A.I. Bolozdynya[1], Yu.V. Efremenko[1,2], K.Scholberg[3]

| | ν flux $sec^{-1}$ | Time structure | Neutrino energy | Distance from the source | Major BG | Signal in detector (Xe) | Event rate in 100 kg Xe detector [10] |
|---|---|---|---|---|---|---|---|
| Reactor | $6 \cdot 10^{20}$ | continuous | Falling from 1 to 7 MeV | 20 m | Cosmic rays | Up to 1 keV | 38000 (400 above reasonable threshold)/day |
| SNS | $3 \cdot 10^{14}$ | Pulsed with duty factor of 1:2000 | DAR shape with endpoint at 53 MeV | 40 m | Fast neutrons from SNS | Up to 20 keV | 2000 (1400 above reasonable threshold)/year |

Complimentary benefits and challenges

# CNNS-related Whitepapers

**Observation of Coherent Neutrino-Nucleus Scattering at a Nuclear Reactor**

S. Sangiorgio, A. Bernstein, J. Coleman, M. Foxe, C. Hagmann, T. H. Joshi, I. Jovanovic, K. Kazkaz, K. Movrokoridis, S. Pereverzev.

**Searches for CENNS at the Spallation Neutron Source**

P. Barbeau, P. Barton, A. Bolozdynya, B. Cabrera-Palmer, F. Cavanna, R. Cooper, G. Greene, Y. Efremenko, E. Figueroa-Feliciano, M. Foxe, A. Hatzikoutelis, R. Hix, D. P. Hogan, I. Jovanovic, S. Klein, J. M. Link, W. C. Louis, D. Markoff, C. Mauger, P. Mueller, K. Patton, H. Ray, D. Reyna, K. Scholberg, R. Tayloe, C. Virtue, J. Yoo

**Measuring CENNS in the Low Energy Neutrino Source at Fermilab**

S. Brice, F. Cavanna, A. Cocco, R. Cooper, Y. Efremenko, L. Garrison, A. Hime, E. Hungerford, B. Loer, S. Pordes, E. Ramberg, H. Ray, K. Scholberg, R. Tayloe, R. Tesarek, H. Wang, J. Yoo and A. Young

**Whitepaper on Cyclotrons as Drivers for Precision Neutrino Experiments**

*The DAEδALUS Collaboration*, January 26, 2013

Notes:

- Value of CNNS observation is clear
- Focus on different sources
- Detector choice is of secondary importance
- Need explicit discussion of long-term reach potential?

# Detectors borrowed from Dark Matter searches

- CNNS detection requirements:
  - Large mass
  - Low energy threshold <1-10 keV, depend on E$\nu$
  - Discrimination of nuclear recoils
- WIMPs detectors have same requirements !!
- CNNS experimental efforts borrow and improve upon WIMP detection techniques
- Some of the names in the game:

Scintillator

- CLEAR (LAr / LNe)

Phonon-Ionization

- RICOCHET (optimized SuperCDMS detectors)

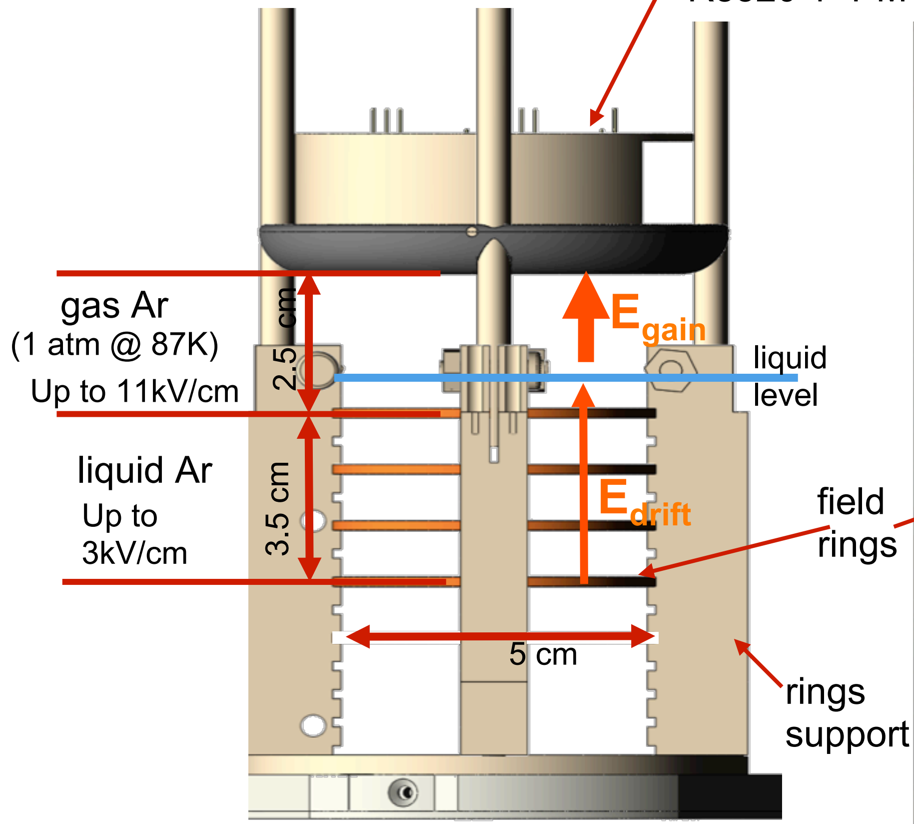
Ionization detectors

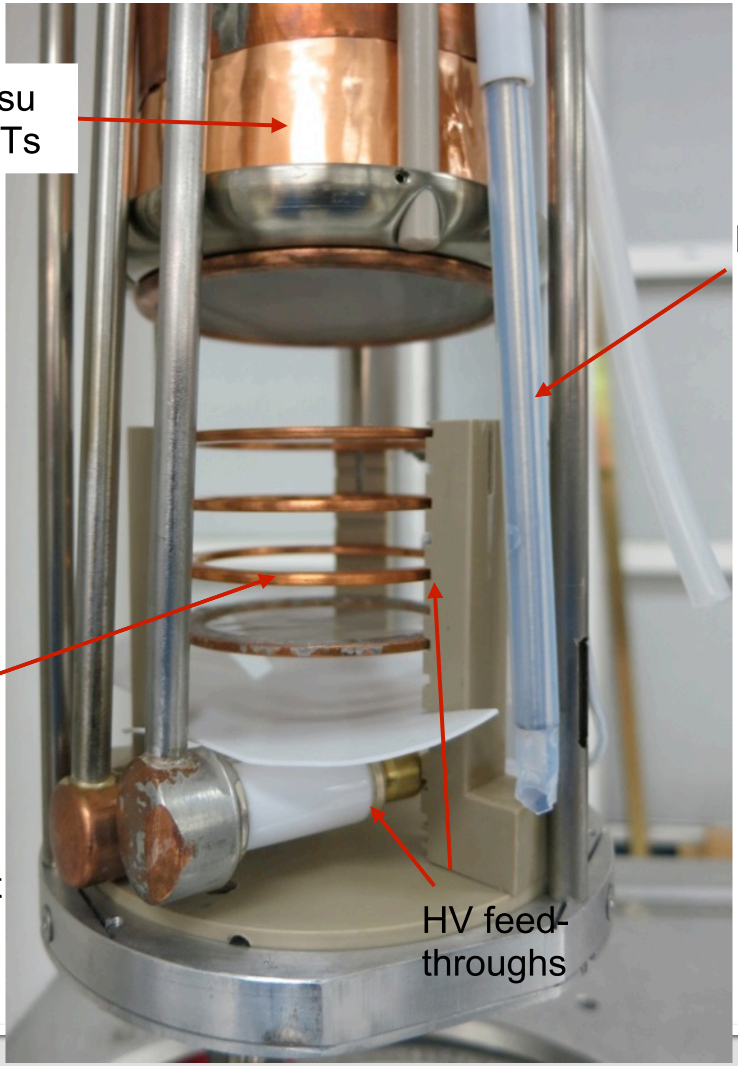
- ULGeN (Ge) (SNL, LBL)
- TEXONO/CDEX (Ge)

- Russian Emission Detector (RED) (Xe)
- LLNL CNNS Detector (Ar)

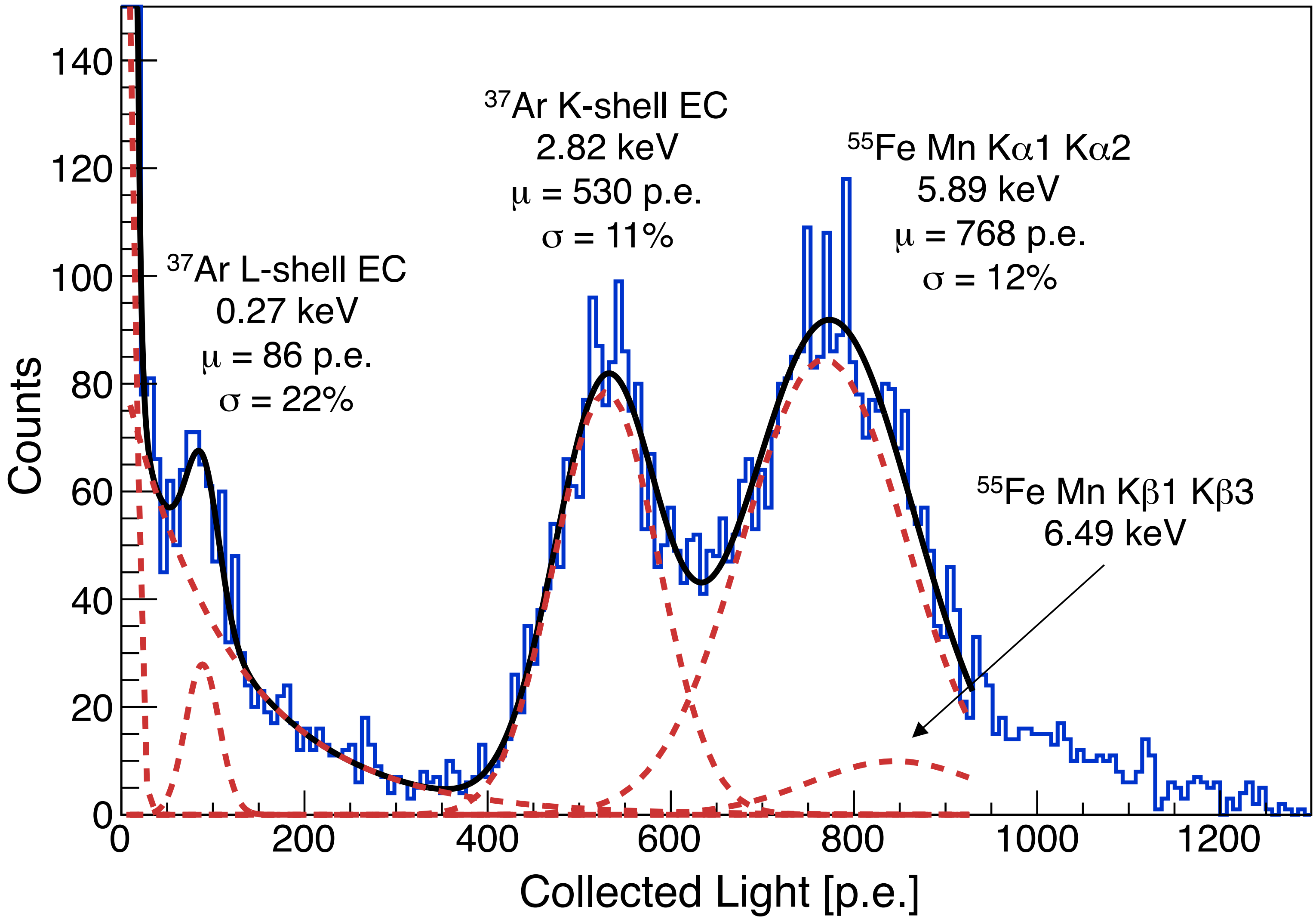
# LLNL Dual-phase Ar Prototype Detector

- Active volume: ~ 100 g LAr
- Focus on high-gain detection of ionization signal only → low energy threshold
- High purity LAr achieved



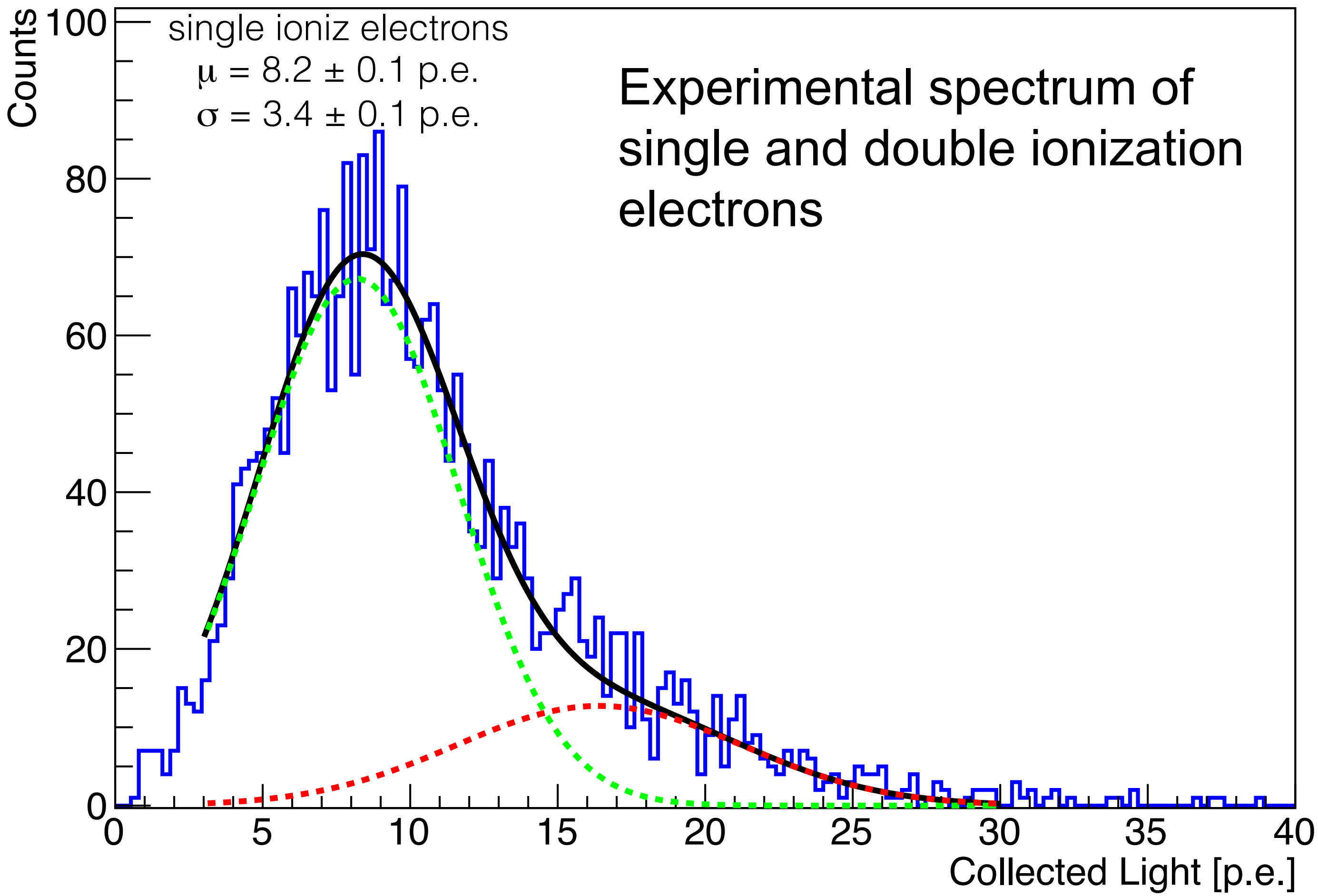
# Sub-keV Sensitivity for Electron Recoils using Novel Calibration Approach Based on $^{37}$Ar




S. Sangiorgio, et al. arXiv:1301.4290

# Detection of Single Ionization Electrons

Ultimate detector sensitivity

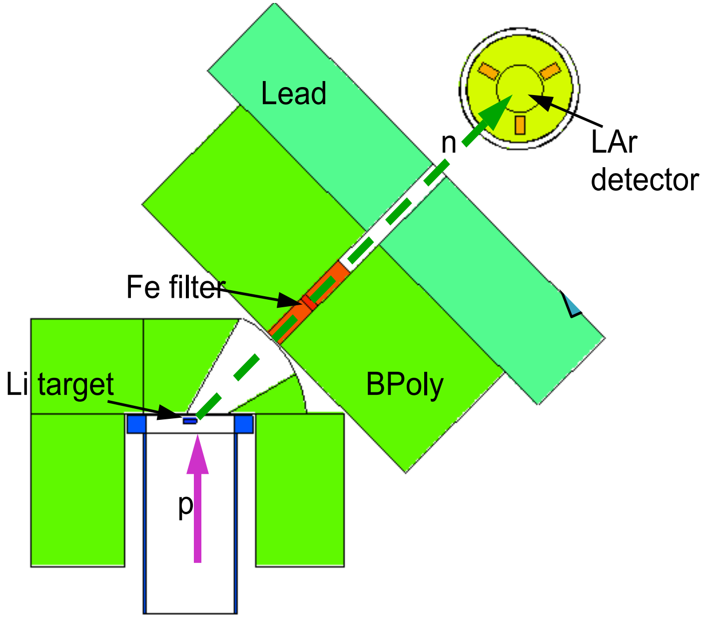


# Ionization Yield of Nuclear Recoil

- Nuclear recoils are less effective than electron recoils in producing ionization
  → Need experimental measurements in liquid nobel gases < few keV

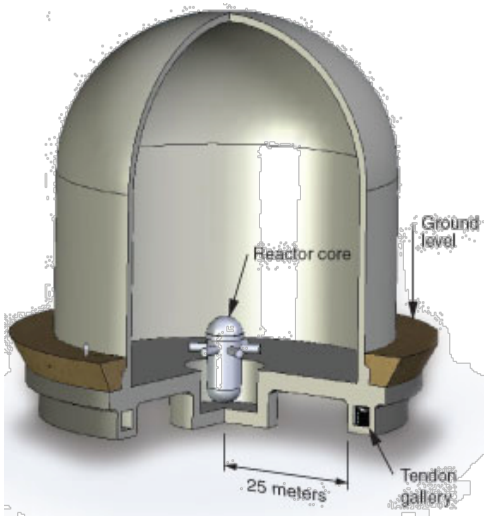
- Key to assess CNNS feasibility of noble-gas detectors with reactor sources
- Planned measurement at LLNL to measure ionization yield in liquid Argon in the ~1-7 keVr range using neutrons
- Use $^{7}Li(p,n)^{7}Be$ reaction near threshold to produce neutrons that are then filtered and collimated to a quasi-monoenergetic beam

LLNL setup for ionization yield measurement with neutrons



# CNNS Application: Nuclear Reactor Safeguards (nu7 subgroup)

- Use of ν for nuclear safeguards demonstrated by LLNL using IBD
- Interest by IAEA
- LLNL Project: design and deploy a 10-kg dual-phase Argon detector

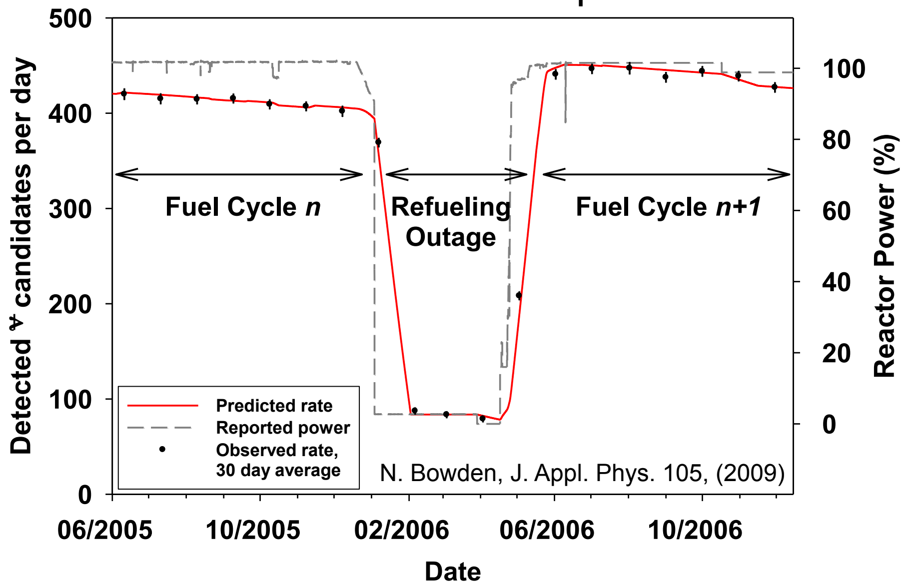



IAEA

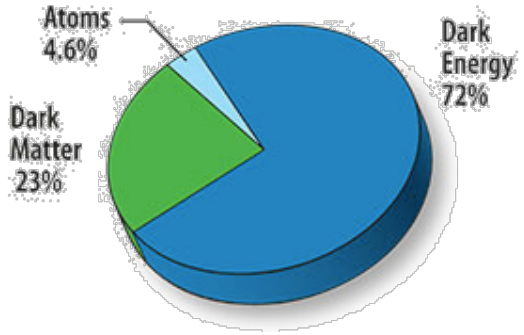
- If signal follows reactor outages, we have confirmation of signal
  - → first observation ever of CNS !
  - → pave the way to use of CNS in reactor monitoring

More on neutrinos and nonproliferation in the next parallel session in Shasta room ($3^{rd}$ floor) 15:00-16:30

Demonstrated via IBD on liquid scintillator

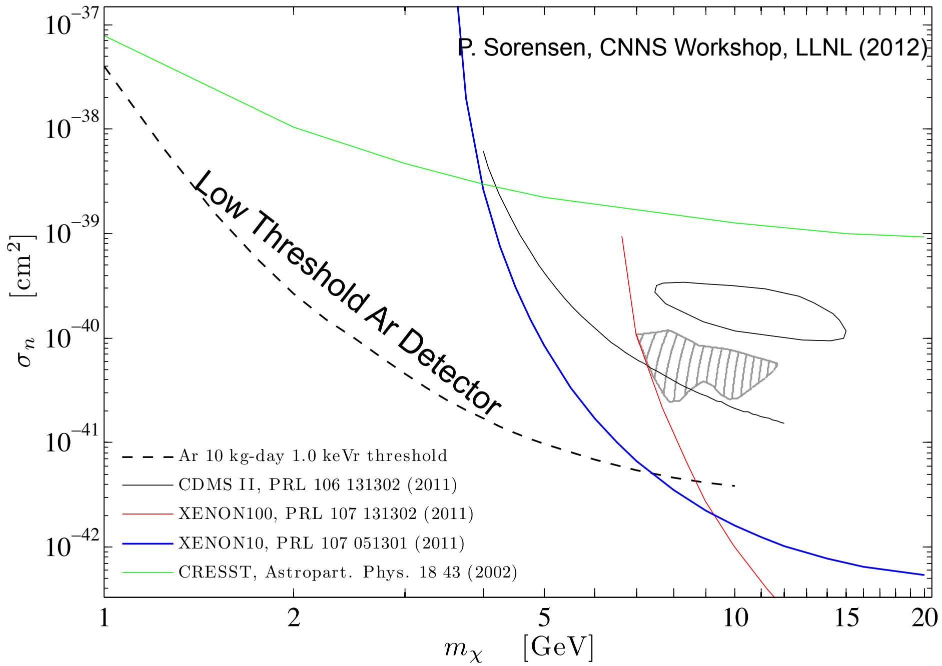


# Synergies with Dark Matter searches and the Cosmic Frontier

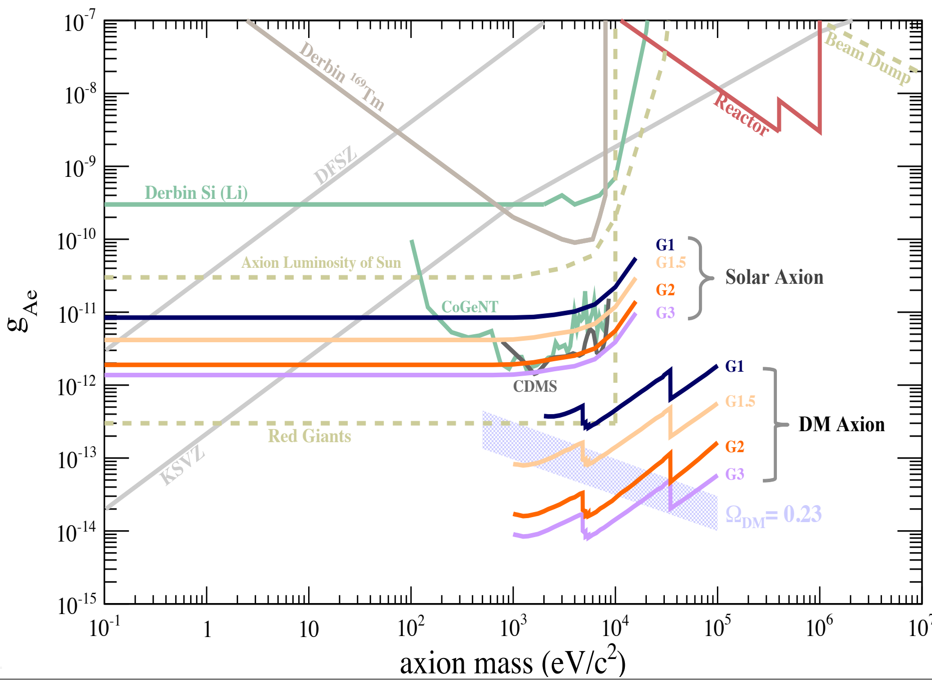



- Direct WIMP detection and CNNS share the same signature (low-E nuclear recoils) and therefore similar detection technology
- Low threshold allows to probe "light" WIMPs candidates and axions

## "Light" WIMP sensitivity



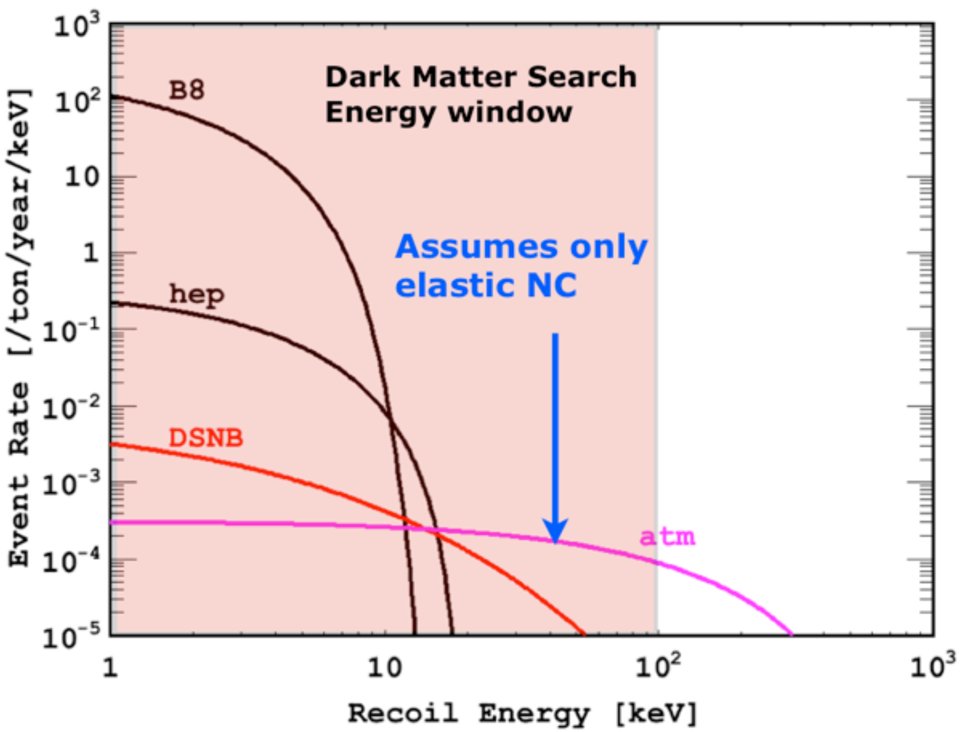

## Axion-electron coupling

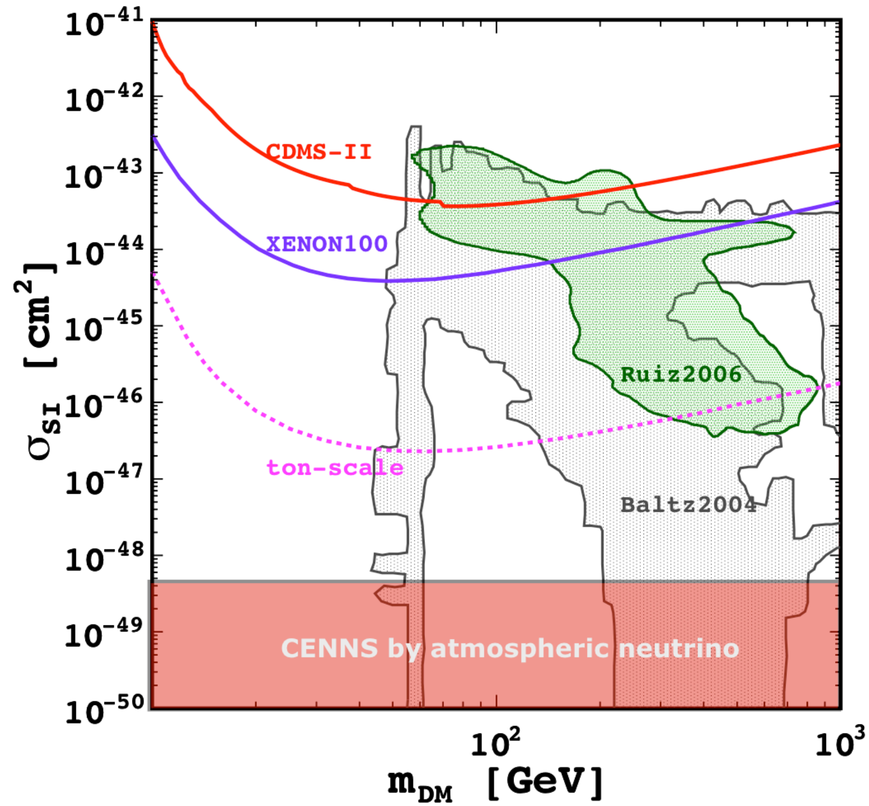


# CNNS as irreducible DM background

Coherent Scatter of solar and atmospheric neutrinos, and DSNB will eventually be an irreducible background for DM experiments

Strigari, arXiv:0903.3630




Plots from J. Yoo, CNNS Workshop, Livermore 2012

# Conclusions

- Growing interest and efforts toward CNNS measurement
  - active community, developing a *coherent* approach

- Phased approach
  - start by demonstrating positive detection
  - move to precision measurements to exploit the scientific potential, starting w/ Supernovae detection, NSI and $\theta_W$

- Neutrino sources: reactor and DAR offer complementary potential and challenges

- Detectors:
  - no longer the limiting factor
  - synergetic R&D w/ Dark Matter

- Links with nu7 (nuclear safeguards) and the Cosmic Frontier

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